

Is there a unique thermal dilepton source in the reactions $\text{Pb}(158 \text{ A}\cdot\text{GeV}) + \text{Au}, \text{Pb}$?

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Abstract

An analysis of the dilepton measurements of the reactions $\text{Pb}(158 \text{ A}\cdot\text{GeV}) + \text{Au}, \text{Pb}$ by the CERES and NA50 collaborations points to a unique thermal source contributing to the invariant mass and transverse momentum spectra.

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Introduction: Dileptons are penetrating probes which carry nearly undisturbed information about early, hot and dense matter stages in relativistic heavy-ion collisions. Some effort, however, is needed for disentangling the various sources contributing to the observed yields and for identifying the messengers from primordial states of strongly interacting matter.

The dielectron spectra for the reaction $\text{Pb}(158 \text{ A}\cdot\text{GeV}) + \text{Au}$ measured by the CERES collaboration [1] cannot be described by a superposition of e^+e^- decay channels of final hadrons, i.e. the hadronic cocktail. A significant additional source of dielectrons must be there. Since the data [1] cover mainly the invariant mass range $M < 1.5 \text{ GeV}$ the downward extrapolation of the Drell-Yan process is not an appropriate explanation. Also correlated semileptonic decays of open charm mesons have been excluded [2]. As a widely accepted explanation, a thermal source is found to account for the data (cf. [3, 4] and further references therein, in particular with respect to in-medium effects and chiral symmetry restoration).

Very similar, the NA50 collaboration has found, for the reaction $\text{Pb}(158 \text{ A}\cdot\text{GeV}) + \text{Pb}$, that the superposition of Drell-Yan dimuons and open charm decays does not explain the data in the invariant mass range $1.5 \text{ GeV} < M < 2.5 \text{ GeV}$ [5]. Final state interactions [6] or abnormal charm enhancement [5, 7] have been proposed as possible explanations. Here

we try to explain the NA50 measurements by another idea [8], namely a thermal source [9, 10], which was already found to account for the data in the intermediate invariant mass range in the reaction S (200 A·GeV) + W [11]. We present a schematic model describing at the same time the CERES and NA50 data.

The model: Since we include the corresponding detector acceptances a good starting point for Monte Carlo simulations is the differential dilepton spectrum

$$\frac{dN}{p_{\perp 1} dp_{\perp 1} p_{\perp 2} dp_{\perp 2} dy_1 dy_2 d\phi_1 d\phi_2} = \int d^4Q d^4x \frac{dR}{d^4Q d^4x} \delta^{(4)}(Q - p_1 - p_2), \quad (1)$$

where $Q = p_1 + p_2$ is the pair four-momentum, $p_{1,2}$ are the individual lepton four-momenta composed of transverse momenta $p_{\perp 1,2}$ and rapidities $y_{1,2}$ and azimuthal angles $\phi_{1,2}$. Here we extensively employ the quark - hadron duality [4, 8, 11, 12] and base the rate R on the lowest-order quark - antiquark ($q\bar{q}$) annihilation rate (cf. [13, 14])

$$\frac{dR}{d^4Q d^4x} = \frac{5\alpha^2}{36\pi^4} \exp \left\{ -\frac{u \cdot Q}{T} \right\}, \quad (2)$$

where $u(x)$ is the four-velocity of the medium depending on the space-time as also the temperature $T(x)$ does. Note that, due to Lorentz invariance, u necessarily enters this expression. The above rate is in Boltzmann approximation, and a term related to the chemical potential is suppressed. As shown in [4] the $q\bar{q}$ rate deviates from the hadronic one at $M < 300$ MeV, but in this range the Dalitz decays dominate anyhow; in addition, in this range the thermal yield is strongly suppressed by the CERES acceptance. In the kinematical regions we consider below, the lepton masses can be neglected.

Performing the space-time and momentum integrations in eqs. (1, 2) one gets

$$\frac{dN}{dp_{\perp 1} dp_{\perp 2} dy_1 dy_2 d\phi_1 d\phi_2} = \frac{5\alpha^2}{72\pi^5} p_{\perp 1} p_{\perp 2} \int_{t_i}^{t_f} dt V(t) E, \quad (3)$$

$$E = \begin{cases} \exp \left\{ -\frac{M_{\perp} \cosh Y \cosh \rho(r,t)}{T(r,t)} \right\} \frac{\sinh \xi}{\xi} & \text{for } 3D, \\ K_0 \left(\frac{M_{\perp} \cosh \rho(r,t)}{T(r,t)} \right) I_0 \left(\frac{Q_{\perp} \sinh \rho(r,t)}{T(r,t)} \right) & \text{for } 2D, \end{cases} \quad (4)$$

$$V(t) = \begin{cases} 4\pi \int dr r^2 & \text{for } 3D, \\ t \int dr r & \text{for } 2D, \end{cases} \quad (5)$$

where $V(t)$ acts on E , and $3D$ means spherical symmetric expansion, while $2D$ denotes the case of longitudinal boost-invariant and cylinder-symmetrical transverse expansion; the quantity ξ is defined as $\xi = T^{-1} \sinh \rho \sqrt{M_{\perp}^2 \cosh^2 Y - M^2}$, and $\rho(r, t)$ is the radial or transverse expansion rapidity; K_0 and I_0 are Bessel functions [13]. The components of the lepton pair four-momentum $Q = (M_{\perp} \cosh Y, M_{\perp} \sinh Y, \vec{Q}_{\perp})$ are related to the individual lepton momenta via

$$M_{\perp}^2 = p_{\perp 1}^2 + p_{\perp 2}^2 + 2p_{\perp 1} p_{\perp 2} \cosh(y_1 - y_2), \quad (6)$$

$$\vec{Q}_\perp = \vec{p}_{\perp 1} + \vec{p}_{\perp 2}, \quad (7)$$

$$M^2 = M_\perp^2 - Q_\perp^2, \quad (8)$$

$$\tanh Y = \frac{p_{\perp 1} \sinh y_1 + p_{\perp 2} \sinh y_2}{p_{\perp 1} \cosh y_1 + p_{\perp 2} \cosh y_2}. \quad (9)$$

It turns out that the shape of the invariant mass spectrum $dN/(dM dY|_{|Y|<0.5} dt dV(t))$, which is determined only by the emissivity function E , does not depend on the flow rapidity ρ in the 2D case [13], and in the 3D case for $T = 120 \cdots 220$ MeV and $\rho < 0.6$ there is also no effect of the flow. The analysis of transverse momentum spectra of various hadrons species point to an average transverse expansion velocity $\bar{v}_\perp \approx 0.43$ [15] at kinetic freeze-out, while a combined analysis of hadron spectra including HBT data yields $\bar{v}_\perp \approx 0.55$ [16]. Therefore, $\rho < 0.6$ is the relevant range for the considered reactions.

We note further that the invariant mass spectra $dN/(dM dY|_{|Y|<0.5} dt dV(t))$ for the 3D and 2D cases differ only marginally. Relying on these findings one can approximate the emissivity function E by that of a "static" source at midrapidity, as appropriate only for symmetric systems,

$$E = \exp \left\{ -\frac{M_\perp \cosh Y}{T(t)} \right\}, \quad (10)$$

thus getting rid of the peculiarities of the flow pattern. We would like to emphasize the approximate character of eq. (10) because once cooling and dilution of the matter are included, they are necessarily accompanied by expansion and flow. One has therefore to check to which degree the flow affects the dilepton observables.

In contrast to the invariant mass spectra, the transverse momentum or transverse mass spectra are sensitive to the flow pattern [13, 17, 18], in general. A value of $\rho = 0.4$, for example, causes already a sizeable change of the shape of the spectra $dN/(dQ_\perp dY|_{|y|<0.5} dt dV(t))$ compared to $\rho = 0$, in particular in the large- Q_\perp region. The differences between the 2D and 3D cases are not larger than a factor of 2 and, in a restricted Q_\perp interval, can be absorbed in a renormalization. The most striking difference of the 2D and 3D scenarios is seen in the rapidity spectrum: for 2D it is flat, while in the 3D case it is localized at midrapidity (values of $\rho < 0.6$ also do not change the latter rapidity distribution). Below we shall discuss which space is left to extract from the dilepton data in restricted acceptance regions hints for the flow pattern when the other dilepton sources are also taken into account.

Comparison with data: In line with the above arguments we base our rate calculations on eqs. (3, 10) and use the parameterizations [19]

$$T = (T_i - T_\infty) \exp \left\{ -\frac{t}{t_2} \right\} + T_\infty, \quad (11)$$

$$V = N \exp \left\{ \frac{t}{t_1} \right\}. \quad (12)$$

with $T_i = 210$ MeV, $T_\infty = 110$ MeV, $t_1 = 5$ fm/c, $t_2 = 8$ fm/c, $N = \frac{A+B}{2.5n_0}$ with A, B as

mass numbers of the colliding systems and $n_0 = 0.17 \text{ fm}^{-3}$. We stop the time evolution at $T_f = 130 \text{ MeV}$.

In fig. 1 we show the comparison with the preliminary CERES data applying the appropriate acceptance [1]. One observes a satisfactory overall agreement of the sum of the hadronic cocktail and the thermal contribution with the data. It is the thermal contribution which fills the hole of the cocktail around $M = 0.5 \text{ GeV}$ in the invariant mass distribution in fig. 1a. In the mass bin $M = 0.25 \cdots 0.68 \text{ GeV}$ the thermal yield is seen (fig. 1b) to dominate at small values of the transverse momentum Q_\perp . In this region of Q_\perp transverse flow effects are not important. The large- Q_\perp spectrum is dominated by the cocktail. For higher-mass bins the thermal yield in the region of the first two data points is nearly as strong as the cocktail and rapidly falls then at larger values of Q_\perp below the cocktail. Therefore, the flow effects turn out to be of minor importance for the present analysis, since within our framework the transverse flow shows up at larger values of Q_\perp .

The question now is whether the same thermal source model accounts also for the NA50 data [5]. In the mass range $M > 1 \text{ GeV}$, the Drell-Yan dileptons and dileptons from correlated semileptonic decays of open charm mesons must be included. To get the corresponding yields for Pb + Pb collisions from PYTHIA [20] the overlap function $T_{AA} = 31 \text{ mb}^{-1}$ is used. We have carefully checked that our PYTHIA calculations with K factors $K_{\text{DY}} = 1.23$ and $K_{\text{charm}} = 4$, adjusted to Drell-Yan data [21] and identified open charm data (cf. [2] for a data compilation), and intrinsic transverse parton momentum $\langle k_\perp \rangle = 0.9 \text{ GeV}$ coincide with results of the NA50 collaboration. In particular, we reproduce with $\chi^2_{\text{d.o.f.}} = 0.24$ the anticipated NA50 result [5] that the data of the most central collisions (except the J/ψ region) are described by the Drell-Yan yield + $2.8 \times$ the yield from correlated semileptonic decays of open charm. In this way we get some confidence in our acceptance routine which essentially consists of geometrical cuts [5] and a suitable minimum single-muon energy of $\mathcal{O}(11.5 \text{ GeV})$ [10].

The resulting invariant mass spectra, including the thermal source contribution, are displayed in fig. 2a. The thermal source, with strength adjusted by the above comparison with CERES data, is needed to achieve the overall agreement with data. For $M < 2 \text{ GeV}$ the thermal contribution dominates over the Drell-Yan and charm contributions. The value of $\chi^2_{\text{d.o.f.}} = 1.38$ quantifies that the very details of the data are not perfectly described. This may be attributed to the too schematic source model eq. (10) and our approximate description of the more involved NA50 acceptance. Nevertheless, the transverse momentum spectrum for the mass bin $M = 1.5 \cdots 2.5 \text{ GeV}$ is nicely reproduced by the sum of Drell-Yan, open charm and thermal contributions with $\chi^2_{\text{d.o.f.}} = 2$. The thermal yield is strongest at not too large values of Q_\perp where transverse flow effects can be neglected. Therefore, it seems that from present dilepton measurements the transverse flow can hardly be inferred. However, a reduction of the above uncomfortably large value

of the phenomenological parameter $\langle k_{\perp} \rangle$ could be partially compensated by transverse flow.

In a previous version of this note [9] we have confronted our model with the findings of the NA50 collaboration according to the recipe "reconstructed data" = the Drell-Yan yield + $3 \times$ the dilepton yield from decays of D mesons and found a much better agreement. This fact points to the need to employ the full acceptance matrix in attempting a decision on the best data interpretation.

Summary and discussion: In summary we have shown that a very simplified, schematic model for thermal dilepton emission, with parameters adjusted to the CERES data, also accounts for the measurements of the NA50 collaboration. Our study points to a common thermal source seen in different phase space regions in the dielectron and dimuon channels. This unifying interpretation of different measurements has to be contrasted with other proposals of explaining the dimuon excess in the invariant mass region $1.5 \dots 2.5$ GeV either by final state hadronic interactions or an abnormally large open charm production. The latter one should be checked experimentally by a direct measurement of D mesons as envisaged in the proposal [7], thus providing a firm understanding of various dilepton sources.

Due to the convolution of the local matter emissivity and the space-time history of the whole matter and the general dependence on the flow pattern, it is difficult to decide which type of matter (deconfined or hadron matter) emits really the dileptons. Our model is not aimed at answering this question. Instead, with respect to chiral symmetry restoration, we apply the quark - hadron duality as a convenient way to roughly describe the dilepton emissivity of matter by a $q\bar{q}$ rate, being aware that higher-order QCD processes change this rate [18, 22] (this might partially be included in a changed normalization N). In further investigations a more microscopically founded rate together with a more detailed space-time evolution must be attempted and chemical potentials controlling the baryon and pion densities must be included. This has been accomplished in [10] to a large extent with similar conclusions as ours.

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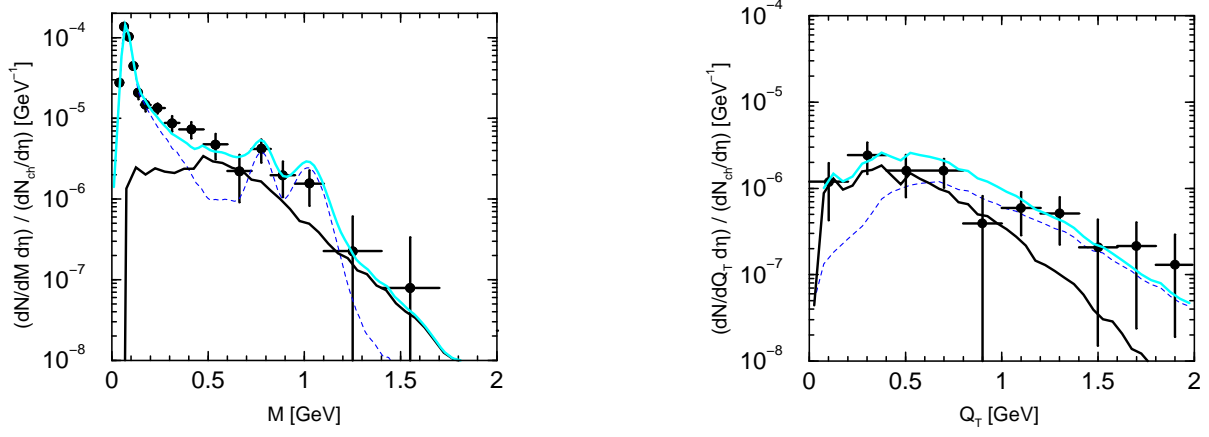


Figure 1: The preliminary CERES data [1] and the hadronic cocktail [1] (dashed lines) and the thermal yield (full curves). The sum of the cocktail and the thermal yield is shown by the gray curves. Left panel (a): the invariant mass spectrum ($\chi^2_{\text{d.o.f.}} = 1.4$), right panel (b): the transverse momentum spectrum for the mass bin $0.25 \cdots 0.68$ GeV ($\chi^2_{\text{d.o.f.}} = .74$).

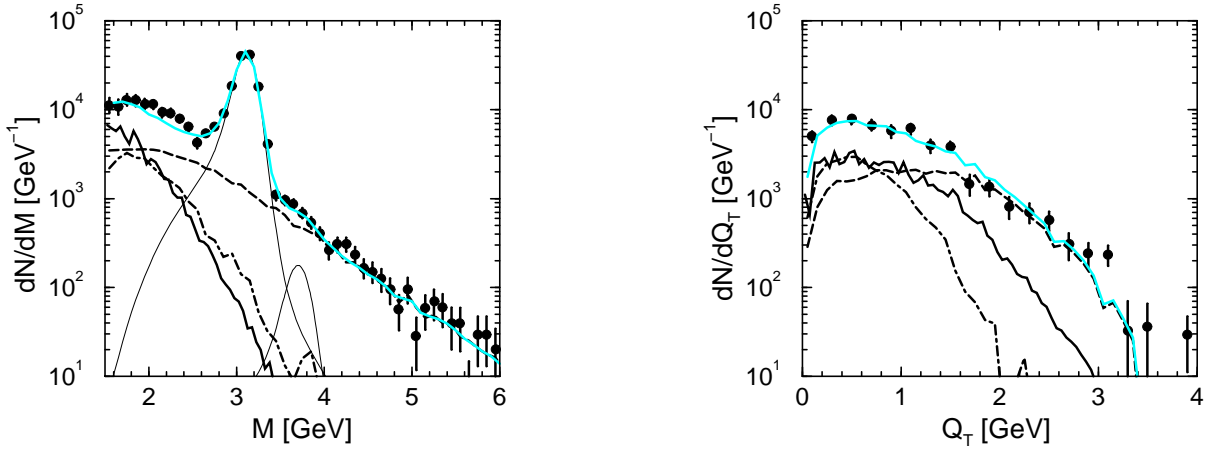


Figure 2: The preliminary NA50 data [5] in comparison with the thermal yield (full curves), the Drell-Yan contribution (dashed curves) and the contribution of open charm decays (dash-dotted curves). The J/ψ and ψ' curves (thin lines) are taken from [5]. The sum of these contributions is displayed by the gray curves. Left panel (a): the continuum invariant mass spectrum, right panel (b): the transverse momentum spectrum for the mass bin $1.5 \cdots 2.5$ GeV.